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RESEARCH MEMORANDUM

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METHOD FOR ESTIMATING COMBUSTION EFFICIENCY AT ALTITUDE FLIGHT CONDITIONS FROM COMBUSTOR TESTS AT LOW PRESSURES

By Walter T. Olson, J. Howard Childs, and Wilfred E. Scull

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RESEARCH MEMORANDUM

METHOD FOR ESTIMATING COMBUSTION EFFICIENCY AT ALTITUDE FLIGHT CONDITIONS FROM COMBUSTOR TESTS AT LOW PRESSURES

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SUMMARY

The development and the use of a chart for use in estimating the combustion efficiency of a turbojet at altitude flight conditions are described. Use of the chart requires that the following data be available for the particular combustor and turbojet engine under consideration: (1) The combustion efficiency must be known from tests of the combustor over a range of conditions to determine the correlation curve of efficiency against the parameter V_r/p_1t_i (where V_r is a combustor reference velocity and p_1 and t_i are the pressure and temperature at the combustor inlet). These combustor tests need not be conducted at conditions simulating the flight conditions of interest. (2) The sea-level, static performance of the turbojet engine must be known to determine the air-flow rate, compressor pressure ratio, and turbine-inlet temperature at various engine speeds.

The combustion efficiency chart is based on the assumption that the corrected gas flows, pressures, and temperatures of engine components other than the combustor are unique functions of corrected engine speed. The validity of the chart is dependent, of course, on the validity of the correlation of combustion efficiency with the parameter V_r/p_it_i, and this correlation is subject to the limitations discussed in this report.

INTRODUCTION

One of the most important effects of altitude on turbojet performance is that of lowered combustion efficiency at the low combustor-inlet pressures and temperatures encountered at high altitude conditions (ref. 1). In reference 2, the effects of combustor-inlet temperature, pressure, and reference velocity on the combustion efficiency of turbojet combustors were correlated by use of the parameter p_it_i/V_r. This parameter correlated the performance of several combustors reasonably well.

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The correlations were of value in predicting the combustion efficiency at different operating conditions and in comparing the performance of different combustors from data obtained in unrelated tests.

The object of the work reported herein was to combine the correlated performance data of combustors at unrelated altitude conditions with data obtained in sea-level, static tests of turbojet engines and to devise a chart for use in estimating the combustion efficiency to be expected at altitude with a given turbojet engine and a given combustor. For such a chart, the following data must be available:

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(1) Data from sea-level, static tests of the turbojet engine over a range of engine rotor speeds

(2) Data from tests of the combustor component over a range of low-pressure conditions to establish the correlation of combustion efficiency with the parameter $V_r/p_i t_i$.

Data on the sea-level, static performance of turbojet engines are normally obtained in early development tests of experimental engines. Necessary data on combustor performance at simulated altitudes can be obtained in a direct-connect duct investigation of the combustor or a part thereof.

The chart should help in estimating the altitude performance of an engine with a combustor for which limited test data are available. It should also help in the selection of one experimental combustor design in preference to another.

No attempt is made in the work presented herein to predict the effect of altitude on engine components other than the combustor. The characteristics of other components are therefore considered constant with variation in altitude.

The chart was developed at the NACA Lewis laboratory.

SYMBOLS

The symbols in this report are listed for ready reference in the following tabulation:

A_r maximum cross-sectional area of combustor flow passages, sq ft

K dimensional constant

M flight Mach number

N	engine rotational speed, rpm
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
R	gas constant for air, 53.3 ft-lb/(lb)(^{o}R)
r	compressor pressure ratio
T	total temperature, ^{o}R
t	static temperature, ^{o}R
V_r	combustor reference velocity (computed from total air flow through combustor, combustor-inlet density, and A_r), ft/sec
W_a	air flow, lb/sec
γ	ratio of specific heat at constant pressure to specific heat at constant volume
θ	ratio of total temperature to temperature of standard NACA air at sea level
δ	ratio of total pressure to pressure of standard NACA air at sea level
$\frac{P_2}{P_0}$	diffuser total-pressure recovery factor

Subscripts:

0	ambient atmosphere
1	diffuser inlet
2	diffuser outlet
alt	altitude
4	combustor inlet
R	rated
SLS	sea-level static
SL,M_0	sea level, at any flight Mach number

DEVELOPMENT OF COMBUSTION EFFICIENCY CHART

The combustion efficiency chart (fig. 1) is based on the correlation of combustion efficiency with the combustion parameter $p_i t_i / V_r$ derived in reference 2. It is shown in reference 3, however, that a plot of combustion efficiency against the reciprocal of this parameter gives a curve which is more convenient for comparison of different combustors.

General Equation

The combustion parameter as used herein may be represented by the expression

$$\frac{V_r}{p_i t_i} = R \frac{W_a/A_r}{p_i^2} \tag{1}$$

It is evident that

$$\frac{W_a}{A_r} = \left(\frac{W_a}{A_r} \frac{\sqrt{\theta_2}}{\delta_2} \right) \frac{\delta_0}{\sqrt{\theta_0}} \frac{\delta_2}{\delta_0} \sqrt{\frac{\theta_0}{\theta_2}} \tag{2}$$

Now

$$\sqrt{\frac{\theta_0}{\theta_2}} = 1$$

and

$$p_i = r P_0 \frac{P_2}{P_0} \frac{p_i}{P_i} = 2116 \, r \, \delta_0 \frac{\delta_2}{\delta_0} \frac{p_i}{P_i} \tag{3}$$

Substituting equations (2) and (3) in equation (1), cancelling terms, and combining constants yield

$$\frac{V_r}{p_i t_i} = K \frac{\left(\frac{W_a}{A_r} \frac{\sqrt{\theta_2}}{\delta_2} \right)}{\left(r \frac{p_i}{P_i} \right)^2 \frac{P_2}{P_0} \delta_0 \sqrt{\theta_0}} \tag{4}$$

Equation (4) expresses the general form of the combustion parameter $V_r/p_i t_i$.

Section I. - For constant $N/\sqrt{\theta}$, $W_a\sqrt{\theta}/\delta$ and P/δ are constant. Thus,

$$\frac{W_a}{A_r}\frac{\sqrt{\theta_2}}{\delta_2} = \left(\frac{W_a}{A_r}\right)_{SLS}$$

and

$$\left(\frac{r\ p_i}{P_i}\right) = \left(\frac{r\ p_1}{P_i}\right)_{SLS}$$

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Also, $P_1 \approx p_i$. Substituting these values and the values of δ_0 and θ_0 with $\gamma = 1.4$ in equation (4) yields

$$\frac{V_r}{p_i t_i} = \frac{K\left(\frac{W_a}{A_r}\right)_{SLS}}{r_{SLS}^2 \frac{P_2}{P_0}\frac{p_0}{p_{SLS}}\sqrt{\frac{t_0}{t_{SLS}}}\,(1 + 0.2\,M_0^2)^4} \tag{5}$$

For sea-level operation, equation (5) reduces to

$$\left(\frac{V_r}{p_i t_i}\right)_{SL,M_0} = \frac{K\left(\frac{W_a}{A_r}\right)_{SLS}}{r_{SLS}^2 \frac{P_2}{P_0}\,(1 + 0.2\,M_0^2)^4} \tag{6}$$

Equation (6) was used to obtain the curves in section I of the combustion efficiency chart (fig. 1). The ordinate scale for the curves in section I is based upon the sea-level values of the combustion parameter for various flight Mach numbers; various sea-level, static compressor pressure ratios; a constant sea-level, static air-flow rate per unit cross-sectional area (W_a/A_r) of 25 pounds per second per square foot; and a diffuser total-pressure recovery factor of 0.95.

Section II. - From equation (6), it is evident that the value of the combustion parameter at sea-level conditions varies directly with sea-level, static air flow through the engine if the other factors in the equation remain constant, or

$$\left(\frac{V_r}{p_i t_i}\right)_{SL,M_0} \propto \left(\frac{W_a}{A_r}\right)_{SLS} \tag{7}$$

The curves in section II of figure 1 were obtained by use of equation (7). The abscissa scale of section II is based upon the sea-level values of the combustion parameter at any flight Mach number; sea-level, static compressor pressure ratio; or sea-level static W_a/A_r.

Section III. - The effect of altitude on the combustion parameter can be expressed by equation (5), which can be reduced to the following equation, if all other factors in the equation remain constant:

$$\left(\frac{V_r}{p_i t_1}\right)_{alt,M_0} = \left(\frac{V_r}{p_i t_1}\right)_{SL,M_0} \frac{p_{SLS}}{p_0} \sqrt{\frac{t_{SLS}}{t_0}} \qquad (8)$$

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Equation (8) was used to obtain the curves in section III of figure 1. The ordinate scale in section III is based upon the altitude value of the combustion parameter for any flight Mach number; sea-level, static compressor pressure ratio; or sea-level, static W_a/A_r.

Section IV. - Typical combustion efficiency curves for three different turbojet combustors are presented in section IV of figure 1 as functions of the parameter $V_r/p_1 t_i$. These curves, which were obtained from references 2 to 4, represent experimental data obtained in direct-connect duct investigations of the combustors. Curves A and B (refs. 4 and 3, respectively) are for experimental, annular combustors; the data were obtained from tests of one-quarter segments of the combustors. Curve C (ref. 2) is for a production-model tubular combustor.

Assumptions and Accuracy

The assumption that the parameters $W_a\sqrt{\theta}/\delta$ and P_1/δ are unique functions of $N/\sqrt{\theta}$ is equivalent to assuming that the operating characteristics of engine components other than the combustor do not vary with changes in altitude. Reference 5 shows that altitude variations have a negligible effect upon corrected turbine gas flow and turbine efficiency. However, at high altitudes, compressor efficiency and corrected compressor air flow are shown to be definite functions of Reynolds number index, decreasing somewhat with decreasing indices, that is, with increasing altitude. The combustion efficiency chart is therefore not accurate when used for those engines in which marked variations in compressor or turbine performance occur with variations in flight altitude.

A constant value of 0.95 was assumed for the total-pressure recovery factor. This value is the ratio of the total pressure at the diffuser outlet to the free-stream total pressure at the diffuser inlet.

The combustion efficiency chart can only be as accurate as the correlation of combustion efficiency with the parameter $V_r/p_i t_i$. As discussed in reference 2, a different correlation curve is obtained for each combustor and for each fuel. For many combustors, the correlation is quite good, the data scatter being within the limits obtained in day-to-day operation at the same test conditions. For some combustors, however, the correlation is not satisfactory. One cause of unsatisfactory correlation may be the dependence of combustor efficiency on fuel-air ratio. Many combustors give a substantially constant efficiency for a range of fuel-air ratios (ref. 2). However, reference 6 shows that, when the fuel-air ratio has a marked effect on the combustion efficiency, the parameter $V_r/p_i t_i$ sometimes gives a good correlation if correlation curves are drawn for narrow ranges of fuel-air ratio. When this technique is used, a family of curves is obtained in section IV of figure 1 for each combustor and fuel. It then becomes necessary to use the curve corresponding to the fuel-air ratio estimated for the particular operating conditions under consideration. However, only one curve is plotted for each combustor in section IV of figure 1, since the combustion efficiencies of these combustors were relatively insensitive to fuel-air ratio.

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The correlation curve of combustion efficiency against the parameter $V_r/p_i t_i$ must be known from experimental investigation of the combustor and fuel under consideration. If the correlation is good and the data points show the variations of combustor operating conditions (p_i, t_i, V_r, and fuel-air ratio) over the entire range of interest, the chart should give reliable predictions of combustion efficiencies.

A large copy of the combustion efficiency chart is attached to this this report. Section IV of the large chart is left blank in order that the reader may plot performance curves for particular combustors of interest. Examples of the use of the chart are included in the appendix.

CONCLUDING REMARKS

The combustion efficiency of a combustor in a given turbojet engine may be estimated for simulated flight conditions if the effects of combustor-inlet pressure, temperature, and reference velocity on combustion efficiency can be correlated by use of the parameter $V_r/p_i t_i$. Necessary data for this estimate, in addition to the data from unrelated tests with the combustor, are the sea-level, static compressor pressure ratio and air flow for the engine over a range of engine rotor speeds. Since corrected pressure P/δ and the corrected air flow $W_a\sqrt{\theta}/\delta$ are constant with variations in flight Mach number or altitude for a constant corrected engine speed $N/\sqrt{\theta}$, the combustion parameter $V_r/p_i t_i$ can

relate combustor and flight conditions. This relation is derived and utilized herein for the construction of a chart that can be used to estimate the combustion efficiency of a given combustor for flight conditions of a given turbojet engine.

The limitations of the chart are dependent upon the validity of the correlation of combustion efficiency with the parameter $V_r/p_i t_i$ and the applicability of corrected terms for pressure, air flow, and engine speed.

The uses of the chart include the approximation of the combustion efficiency to be expected in practice from combustor performance data obtained in tests at conditions which do not simulate flight operation.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 4, 1953

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APPENDIX - EXAMPLES OF USE OF CHART

Example 1. - A turbojet engine is under development. The sea-level, static performance of the engine is known. From direct-connect duct investigations of a single tubular combustor proposed for use in the engine, the performance curve C in section IV of figure 2 was determined. The problem: What is the combustion efficiency to be expected at 60,000 feet, rated speed, and a flight Mach number of 0.6?

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The chart must be used for a constant value of $N/\sqrt{\theta_2}$. At 60,000 feet and a flight Mach number of 0.6, $\sqrt{\theta_2} = 0.901$; if the efficiency at rated speed N_R at 60,000 feet is to be obtained, then the sea-level, static values of r and W_a/A_r used in reading the chart must be obtained for the same value of $N/\sqrt{\theta_2}$. Since $\sqrt{\theta_2} = 1$ for sea-level, static operation, the required value of rated, sea-level, static engine speed is $N_R/0.901$ or $1.11\ N_R$. At an actual engine speed of 11.0 percent above normal rated speed, the sea-level, static compressor pressure ratio r is 5.86; and the engine air flow gives a value of W_a/A_r of 24.6 pounds per second per square foot; these values are from the known sea-level, static performance of the engine and the size of the combustors.

Enter the chart (fig. 2) at a value of 5.86 on the abscissa of section I and move upward to the Mach 0.6 curve (follow the dashed line ab in fig. 2). From the Mach 0.6 curve, move horizontally (line bc) into section II to the line corresponding to $W_a/A_r = 24.6$. Next, move downward (line cd) to the 60,000-foot line in section III. Next, move horizontally (line de) to the combustor performance curve (curve C) in section IV. Finally, move downward to read the combustion efficiency (75.5 percent) from the abscissa of section IV. This value, 75.5 percent, is the combustion efficiency to be expected at 60,000 feet, rated speed, and a flight Mach number of 0.6.

Example 2. - From an experimental investigation of a turbojet combustor, a correlation curve of combustion efficiency against the parameter V_r/p_1t_i has been established. This curve is the curve labeled A in section IV of figure 2. The test conditions investigated in establishing the correlation curve did not simulate flight operation of the combustor. The problem: What is the maximum altitude for cruise (85 percent rated speed) with a combustion efficiency of 95 percent when this combustor is used in a turbojet engine having a compressor pressure ratio of 5.25 at sea-level rated speed? The flight Mach number of interest is 0.6.

Since the maximum altitude for an efficiency of 95 percent is expected to be above the tropopause, $\sqrt{\theta_2} = 0.901$ (example 1) and the corrected engine speed to be used in reading the combustion efficiency chart is

$$\frac{N}{\sqrt{\theta_2}} = \frac{0.85\ N_R}{0.901} = 0.943\ N_R$$

At $0.943\ N_R$, the sea-level, static compressor pressure ratio for the turbojet engine of interest is 4.87 according to the established performance data for the engine. Enter section I of figure 2 at a value of 4.87 for sea-level, static compressor pressure ratio and move upward to the curve corresponding to a flight Mach number of 0.6 (line a'b' in fig. 2). Next, move horizontally to the curve in section II which gives the sea-level, static value of W_a/A_r for the value of $N/\sqrt{\theta_2}$ of interest. The value of W_a/A_r can be computed if the size of the combustor and the sea-level, static air-flow rates produced by the engine are known. The sea-level, static air-flow rate at this engine speed ($0.943\ N_R$) is 92.4 pounds per second for the turbojet engine of interest. The maximum cross-sectional area of the combustor flow passages, if the combustor is not to exceed the size of the compressor of the engine, is 5.06 square feet. This gives a value of 18.25 for W_a/A_r. Therefore, move horizontally into section II to a value of 18.25 for W_a/A_r (line b'c' on fig. 2), and then move downward into section III (line c'd' on fig. 2). Finally, draw a horizontal line (line e'f' on fig. 2) into section III from the point on curve A in section IV which corresponds to 95 percent combustion efficiency. The intersection of line e'f' with line c'd' gives a value of 68,000 feet in section III of figure 2. This value of 68,000 feet is the maximum altitude at which a combustion efficiency of 95 percent may be obtained at cruise speed when the experimental combustor and the turbojet engine considered are used.

Example 3. - A turbojet engine for which the performance characteristics are well known is to be altered to improve its altitude combustion efficiency. The increased efficiency is to be achieved by using an experimental combustor which gives higher efficiencies and by increasing the frontal area of the combustor. It is assumed that the combustor can be enlarged without its performance being changed. The problem: What is the required combustor frontal area to achieve a combustion efficiency of 95 percent at 50,000 feet and 82 percent rated speed at a flight Mach number of 0.8? The performance of the combustor to be used in the engine is described by curve B in section IV of figure 2. Since the flight altitude of interest is above the tropopause, $\sqrt{\theta_2} = 0.923$. The corrected engine speed at the flight condition of interest is

$$\frac{N}{\sqrt{\theta_2}} = \frac{N_R\ 0.82}{0.923} = 0.889\ N_R$$

The engine sea-level, static performance curves for this speed give a sea-level, static compressor pressure ratio of 2.68. Enter the combustion efficiency chart at a value of 2.68 on the abscissa of section I and move upward to the Mach 0.8 curve (dotted line a"b" in fig. 2). Then move horizontally into section II (dotted line b"c" in fig. 2). Next, begin at the 95-percent efficiency point on curve B in section IV, which represents the performance of the experimental combustor to be used in the engine, and move horizontally to the altitude of interest (50,000 ft) in section III (dotted line d"e" in fig. 2). From the 50,000-foot curve, move vertically into section II (dotted line e"f" in fig. 2). The intersection of line e"f" with line b"c" in section II determines the sea-level, static value of W_a/A_r necessary if the desired performance is to be achieved. This value of W_a/A_r is 11.9 pounds per second per square foot.

At the value of $N/\sqrt{\theta_2}$ of interest (0.889 N_R), the sea-level, static air-flow rate for the engine is 42.9 pounds per second. Then the required A_r is 42.9/11.9 = 3.60 square feet. The value of A_r for the production-model combustor in use with this engine is 2.92 square feet. Therefore, in order to achieve the desired performance, two changes in combustor design are required: (1) The combustor geometry must be altered to that corresponding to the experimental combustor, and (2) the combustor frontal area must be increased to change A_r from the existing 2.92 square feet to 3.60 square feet.

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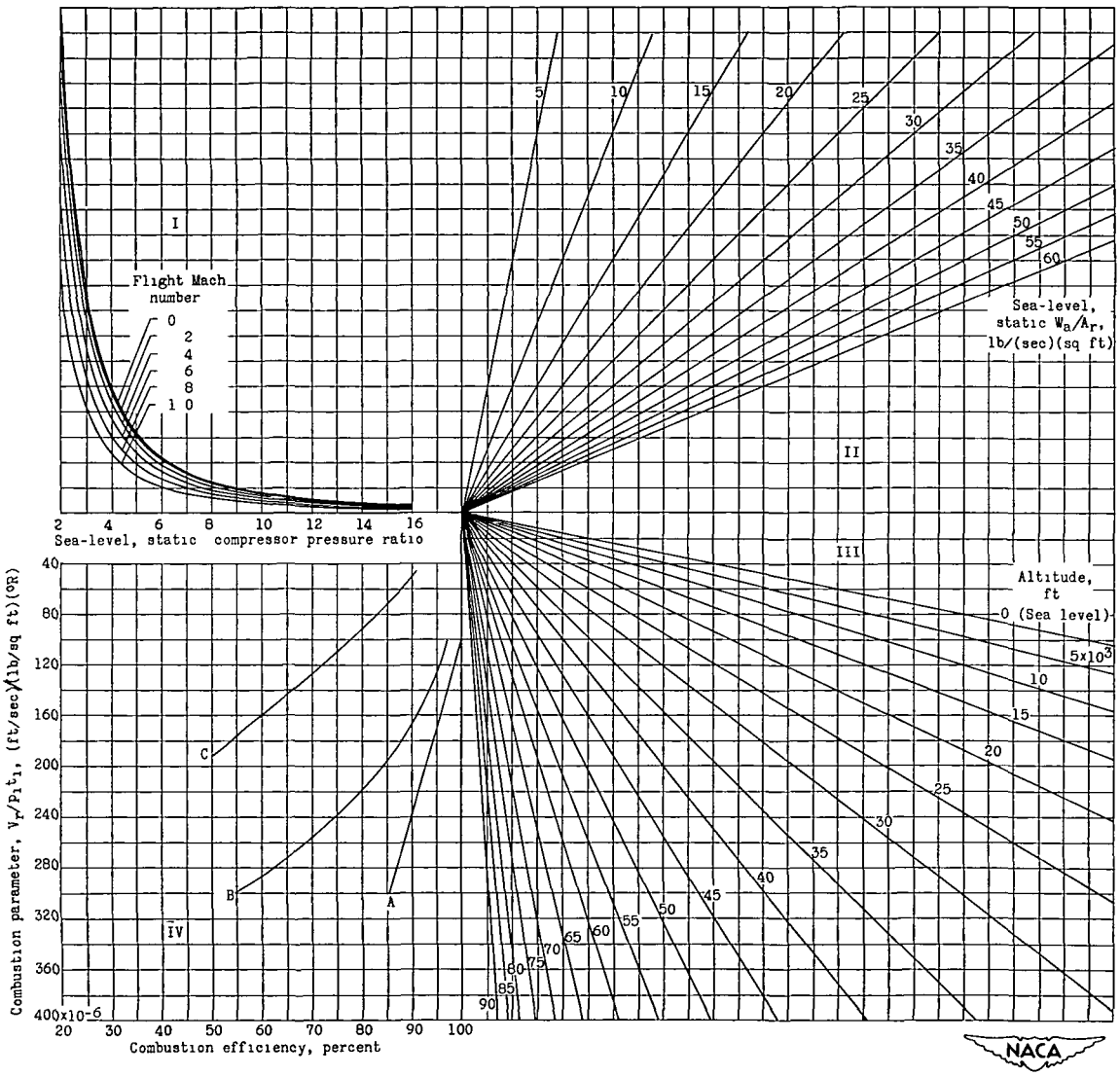


Figure 1 - Combustion efficiency chart Corrected engine speed, constant, diffuser total-pressure recovery factor, 0 95

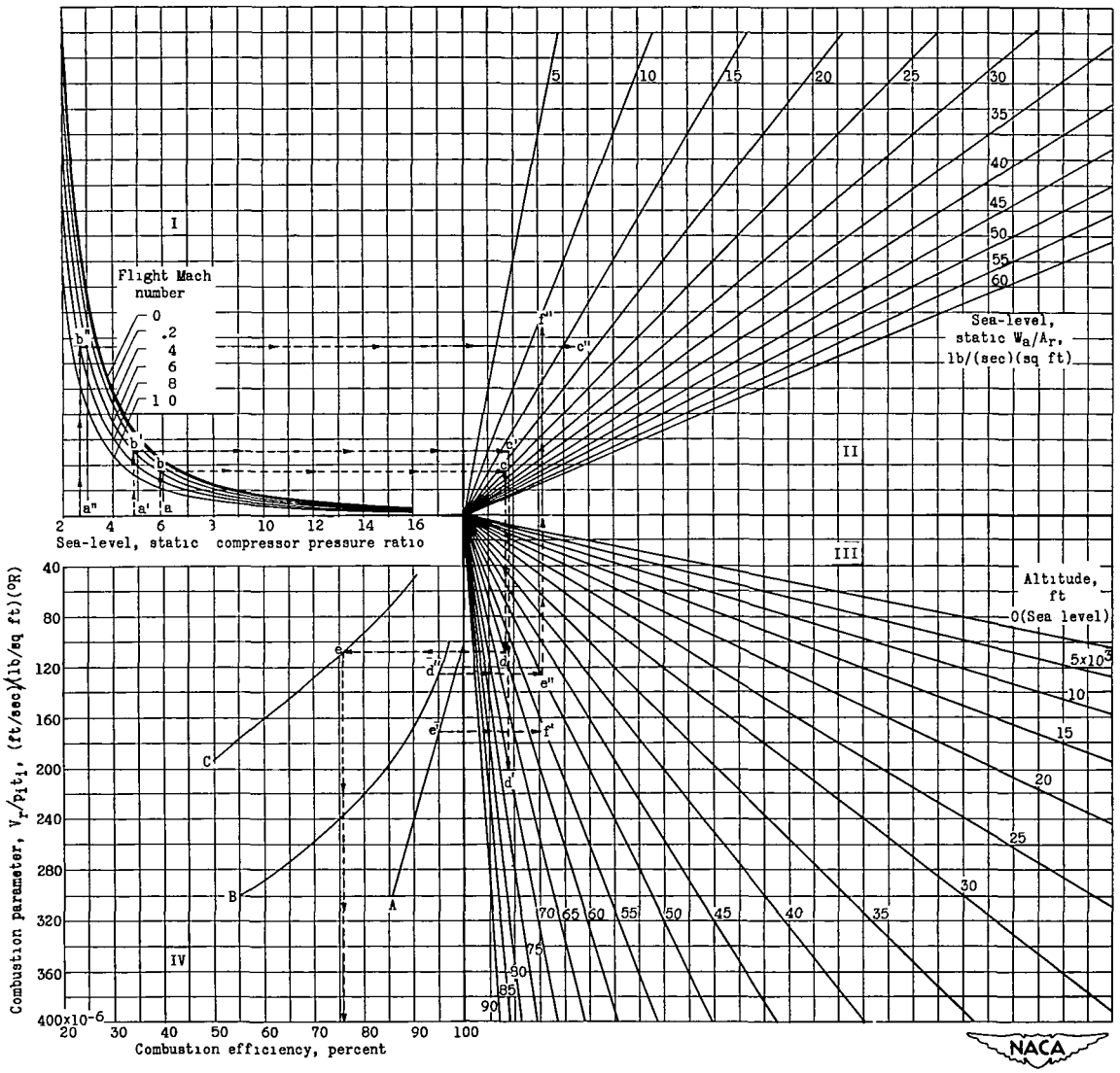
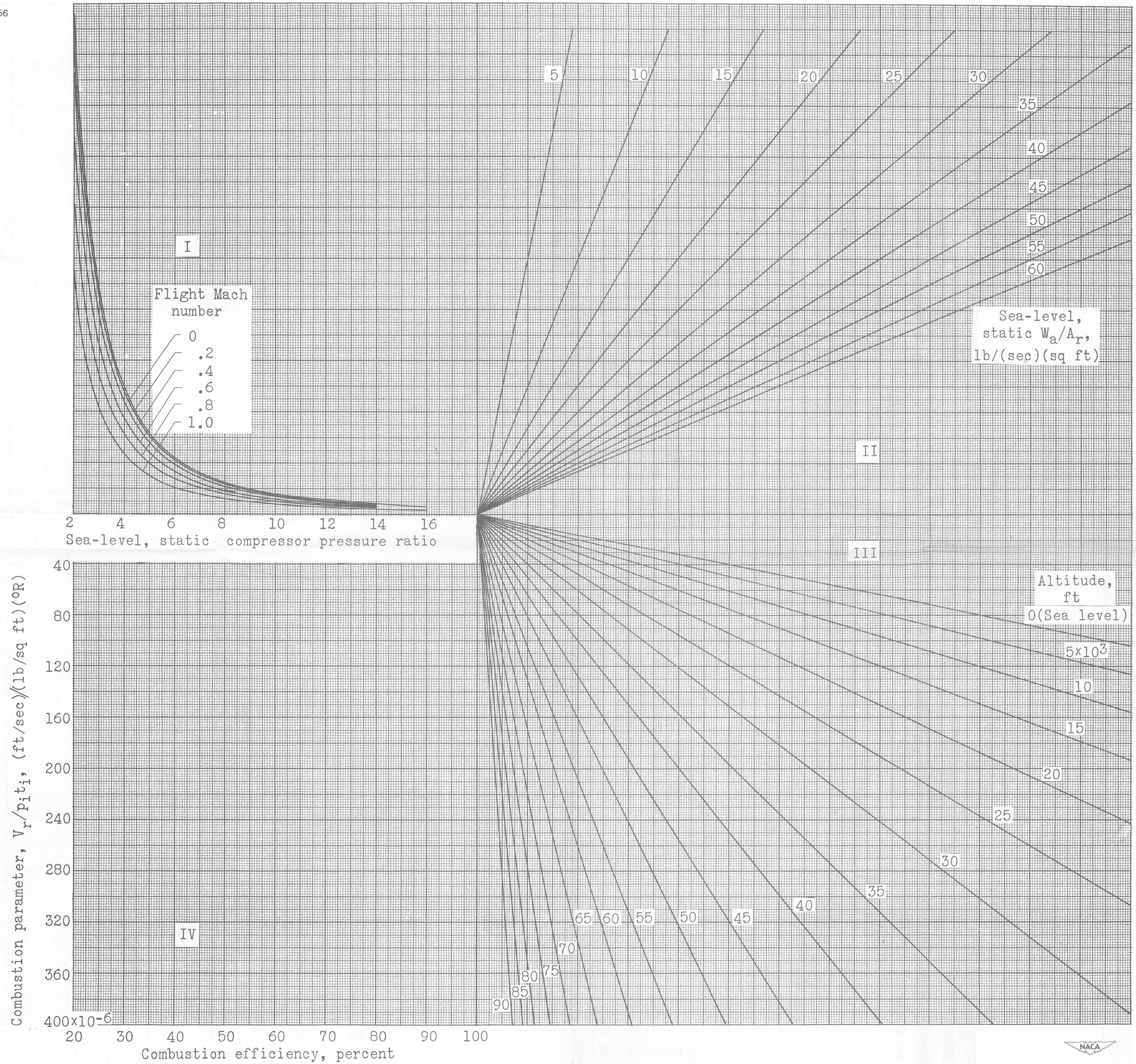


Figure 2 - Examples of use of chart Corrected engine speed, constant, diffuser total-pressure recovery factor, 0 95

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Corrected engine speed, constant; diffuser-total pressure recovery factor, 0.95.

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